

A test system and supervisory control and data acquisition application with programmable logic controller for thermoelectric generators

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ABSTRACT

In this study, a new test measurement system and supervisory control and data acquisition application with programmable logic controller has been carried out to be able the collection of the data of thermoelectric generator for the usage of thermoelectric modules as thermoelectric generator. During the production of the electric energy from the thermoelectric generator, the temperatures of the surfaces of the thermoelectric generator, current–voltage values obtained from output of the thermoelectric generator, hot and cold flows have been measured by the newly established system instantly. All these data have been monitored continuously from the computer and recorded by a supervisory control and data acquisition program. At the same time, in environments where there was no computer, an operator panel with the ability to communicate with the programmable logic controller has been added for the monitoring of the instant thermoelectric generator data. All of the measurement data of the thermoelectric generator have been aggregated in the new test measurement and supervisory control and data acquisition system. The setup test measurement system has been implemented on the thermoelectric generator system with about 10 W. Thermoelectric generators, Altec-GM-1 brand-coded have been examined by the new proposed test measurement system and the values of maximum power and thermoelectric generator efficiency were calculated by the programmable logic controller. When the obtained results were compared with the datasheets, the relative error for the maximum power was around 4% and the value for efficiency was below 3%.

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1. Introduction

Mankind's need for energy keeps increasing day by day. Due to the limited availability of fossil fuels such as petrol, coal used nowadays, people are increasing their efforts for the increase of renewable energy sources as well as more efficient usage of the energy resources [1]. When one considers the increase of human population in the world, the increase in the share of the new and renewable energy sources in energy production and efficiently use of energy are inevitable. When one considers the greenhouse gas effect on the environment by fossil fuels, the importance of renewable and environmentally friendly energy resources becomes more clearer [2]. Today, the studies of energy production from renewable energy sources such as wind, solar, biomass, hydro, geothermal and hydrogen continues rapidly. Thermoelectric generators (TEGs) are used to convert geothermal energy, which is one of the renewable energy sources available, into electrical energy [3]. The basic principle of the TEGs is the Seebeck effect, which was discovered in 1821 by Thomas Seebeck. Since TEGs have no moving mechanical parts, they are long-lived, silent, and environ-

mentally friendly and they require little maintenance [4]. On the other hand, due to the low conversion efficiencies (about 5%) thermoelectric power applications are restricted [5]. Currently, many researches are focused on the increasing of the conversion efficiency of thermoelectric materials. One exception is the TE recovery of waste heat in which it is unnecessary to consider the cost of the thermal input. Consequently, low conversion efficiency is not a serious drawback [6]. A thermoelectric module (TEM) is composed of a number of thermoelements (from 3 to 127) connected electrically in series to increase the operating voltage and thermally in parallel to increase the thermal conductivity. TEGs convert thermal energy into electrical energy directly (Seebeck effect) [7].

Many different measurement instruments have been used for data acquisition and testing of the TEGs. Hand-held measuring instruments usually have been preferred to measure instantaneous values. Data acquisition cards have been used in order to transfer data obtained from the TEG experiments to a personal computer (PC). In order to register the data obtained from the TEGs in the PC, either a separate PC program is written or ready PC programs are often used. Gould et al. [8] designed a thermoelectric test system suitable for conducting experiments to measure the micro-electrical and power generation performance of thermoelectric modules. Their hardware was consisted of standard PC running National Instruments LabView software, data acquisition (DAQ) PC card, Pico

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Table 1

The advantages and differences between our new measurement system and the other measurement systems.

Works-related	The ability of the used measuring system											
	PLC DAQ card or data logger	SCADA	Real-time Monitoring & Recording	Independent on a PC	Monitoring	Recording	Graphics	Hot flow measurement	Cold flow measurement	Temperature measurement	Current measurement	Voltage measurement
Gould et al. [8]	–	+	–	+	–	+	+	–	–	+	+	+
Eklund et al. [9]	+	–	–	–	–	+	+	–	–	+	+	+
Han et al. [10]	–	+	–	+	–	+	+	–	–	+	+	+
Kim [11]	–	+	–	+	–	+	+	–	–	+	+	+
Hasebe et al. [12]	–	+	–	+	–	+	+	–	–	+	+	+
Singh et al. [13]	–	+	–	+	–	+	+	–	–	+	+	+
Champier et al. [14]	–	+	–	–	–	+	+	–	–	+	+	+
Kucukkomurler [15]	–	–	–	–	+	+	–	–	–	+	+	+
Zhou et al. [16]	–	–	–	–	–	+	–	–	–	+	+	+
Rinalde et al. [17]	–	–	–	–	–	+	–	–	–	+	+	+
Our system	+	–	+	+	+	+	+	+	+	+	+	+

Technology thermocouple data logging unit, a number of K-type thermocouples. This system was tested for Melcor module CP1.4-127-05L TEG. Eklund et al. [9] used the DAQ board. Han et al. [10] stored the experimental data in a DAQ device (Yokogawa, DA100) for analysis, after reaching a steady state in the temperature and the voltage output in the TEG system. Kim [11] and Hasebe et al. [12] monitored temperatures of the heater, the heat sink base, and the ambient by utilizing K-type thermocouples, a data logger (Agilent 34970A) and a DAQ PC. Singh et al. [13] and Champier et al. [14] monitored all data of TEGs by a data logger and two hand-held measuring instruments. Kucukkomurler [15], Zhou et al. [16] and Rinalde et al. [17] used the hand-held measuring instruments. The advantages and differences between our new measurement system and the other measurement systems are given in Table 1. Positive signs and negative signs are shown that our proposed measurement system has particular measurement features where the other measurement systems do not.

In this study, a data acquisition and test measurement system with programmable logic controller (PLC) has been established for the measuring, testing, registering and analyzing of the data obtained from the TEGs. All of the measurement data of the thermoelectric generator have been aggregated in the new test measurement and supervisory control and data acquisition system. The cold-hot surface temperatures, the fluid flows passed over hot-cold surfaces, the current, the voltage and the power of the TEG have been measured by this data acquisition and test system. The instantly measured values have been monitored by an operator panel (OP) that was connected to the PLC whose program was specially written for this. Also, a supervisory control and data acquisition (SCADA) program has been written in order to monitor and register the measured data values by the PC. All the data values have been visualized by the SCADA program in the PC. At the same time, all the data values have been transferred to the MySQL database to be analyzed. All the data calculations of TEG have been realized both in the OP and in the SCADA programs.

2. Experimental setup

2.1. TEG basic structure

The structure and equivalent circuit of a TEM module is given in Fig. 1. The basic structure of TEG using the electric production is made up of thermoelectric elements. When p and n-type

semiconductors are connected electrically in series and thermally in parallel, a TEM is set off [18]. TEM devices can typically be classified into thermoelectric generators (TEGs) and thermoelectric coolers (TECs). TEGs convert thermal energy from a temperature gradient to electrical energy (Seebeck effect), whereas TECs convert electrical energy into a temperature gradient (Peltier effect) [7].

The electrical equivalent circuit of the TEG consists of an ideal voltage source V and an internal resistance R_{in} . It is similar to the equivalent circuit of a battery. When a temperature difference between surfaces of TEG occurs, a direct voltage (DC) across the TEG is achieved. If a load resistor R_L is connected across the TEG, the electric current passes through the load resistor and an electric power is obtained from the TEG. If the temperature difference between the surfaces of the TEG is increased, the electric power obtained from the TEG increases. The maximum power output obtained from the TEG is obtained when the internal resistor R_{in} value of the TEG equals that of the load resistor R_L . From the standpoint of TEG applications, it is highly desirable to maximize power output [18].

2.2. Experimental installation of TEG

The experimental setup of the TEG is given in Fig. 2. The main parts of the experimental setup of the TEG consists of a TEG system, a hot-cold water circulator obtained from the hot-cold water, an electric heater placed between the TEGs and an auto transformer that controls the heat of electric heater, a load resistor of the TEG, a SCADA system with PLC, sensors and transmitters.

Two TEGs, which are brand-coded Altec-GM-1, have been used in the TEG system. The flat-rolled electric heater, wired with a chrome-nickel wire of 500 W in the size of 5×5 cm, has been used to provide the increased temperatures of hot surfaces of the TEGs. The heater is compressed in the form of a sandwich between two TEGs forming the hot surface temperatures of the TEGs. Hence due to this electric heater, the hot side temperature could rise up to about 200 °C. Two radiators, sized 5×5×0.8 cm, have been used to provide the cold side temperature and through them, cold water from has been passed with the aid of a water circulator. Owing to an established hot-cold water system, the temperature of the cold water could reduce down to about 5 °C. In this study, while the cold side temperature has been kept constant, the hot side temper-

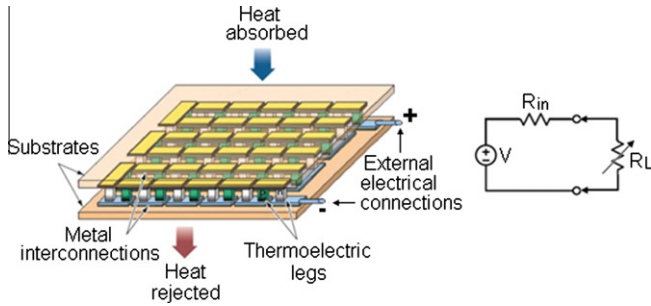


Fig. 1. A TEM in the generator mode and the equivalent circuit of the TEM.

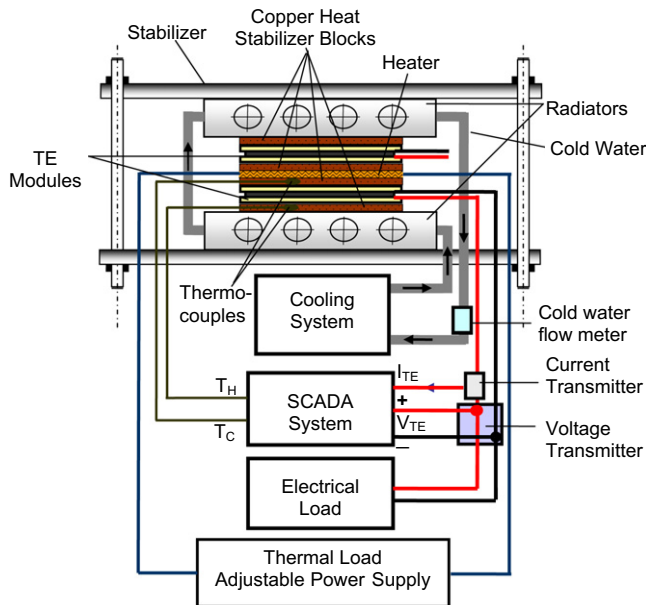


Fig. 2. TEG system block diagram of the experimental setup.

ature has been raised, since power P taken from the TEG depends on the temperature difference ΔT between its surfaces.

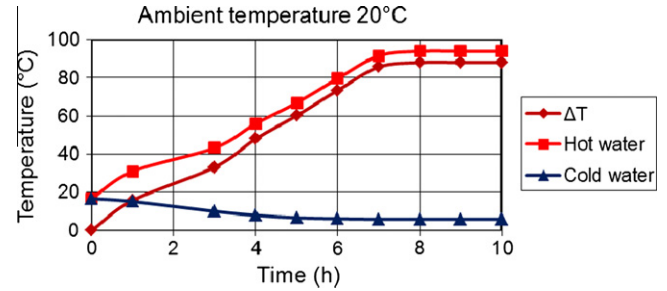


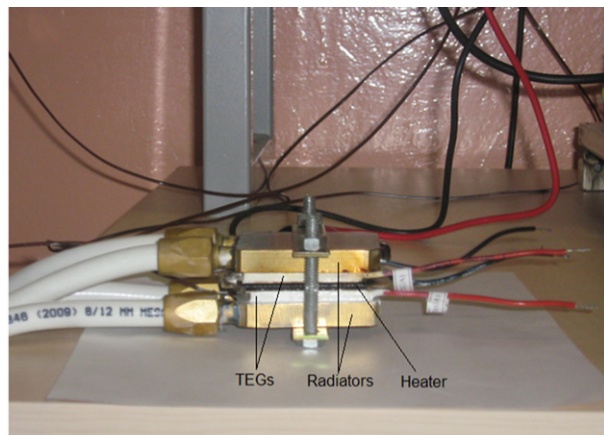
Fig. 4. When the hot-cold water systems are run, interaction of the temperatures of the hot and cold water system.

In order to achieve a higher temperature difference in TEGs, the temperature of the hot surface has been increased by the flat-rolled electrical heater because the temperatures of the hot water, which is provided from geothermal areas, are up to about 95 °C and the value along with the steam temperature reaches about 120 °C. The temperature of the cold water in the application areas is about 15 °C. In this case, the temperature difference between the hot water and the cold water has been raised up to about 100 °C. The temperature difference can be changed through wide ranges of about 250 °C by the flat-rolled electrical heater. Via this, the reactions of the TEGs at the high-temperature have been analyzed. The power of the electric heater has been changed with an auto transformer of 2 kVA with the brand of Artes Electronics Company. The spot-ended T-type thermocouples have been used so as to measure the temperatures of the hot-cold surfaces. Maximum temperature sensing values of T-type thermocouple temperature sensors can be up to 350 °C.

Four copper heat stabilizer plates, with sizes 4×5×0.2 cm, have been placed on each side of the TEGs. Two T-type thermocouples as the temperature sensors have been used in order to sense the temperatures of the hot T_H -cold T_C surfaces of the TEGs and in order to find the temperature difference between the surfaces. As shown in Fig. 2, these thermocouples have been placed onto the copper plate between the TEGs and they have been welded to the heat stabilizer plate. To minimize the thermal conduction resistance between the cold and hot surfaces, silicon grease have been applied to their surfaces. A resistor that is scaled and wound from the chromium-nickel wire of 300 W has been used as the load resistor.



1. Cold water storage tank 4. Refrigerator motors 7. Circulation motors
2. Hot water storage tank 5. On/off controllers 8. Flowmeters
3. Electric heater 6. Hold/cold valves



(a) (b)
Fig. 3. The setup of (a) the hot-cold water circulatory system and (b) the TEMs in TEG mode.

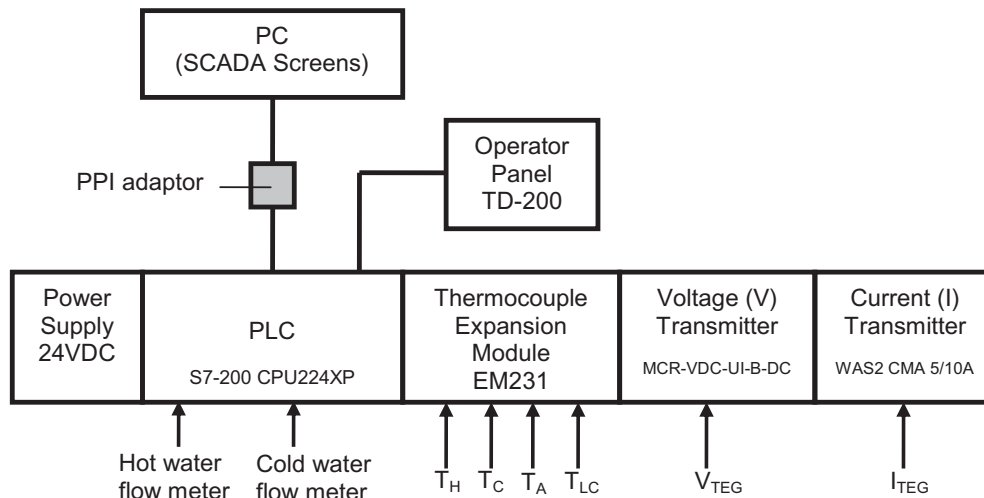


Fig. 5. TEG-DA-TS block diagram.

2.3. The hot–cold water circulator

A hot–cold water circulator system has been established to carry out the TEG experiments in the laboratory, as shown in Fig. 3a. The setup of the TEMs in the TEG mode is given in Fig. 3b. The main parts of the system consisted of a hot water tank, a cold water tank, an electric heater, two cooler motors, two on–off controllers, four hot–cold on–off valves, two hot–cold circulation motors and two flow meters.

In this system, the TEG system of 10 W has been used and later on the TEGs system to be used will be carried out using systems with 100 W and 1.5 kW, as sources of geothermal energy. Performance characteristics of TEG are carried out by maintaining a constant reference value for the temperatures of the hot surface T_H and the cold surface T_C . With this purpose, the developed hot–cold water circulator system can be used both as a source of hot water and as a source of cold water. In order to increase the temperature differences between the TEGs surfaces, the temperature of the cold surface T_C has been lowered as much as possible and kept at the lowest possible levels of about 5 °C.

During the experiments performed, the hot surface temperature of TEG has been provided with the electrical heater to measure the extreme temperature performances of TEG. During application in the field, the hot surface temperature and the cold surface temperature of TEG, to be tested, will be provided with the geothermal hot water and the cold public water supply, respectively. The temperatures of the geothermal resources and the temperatures of the cold public water supply are up to about 120 °C and <20 °C, respectively. Pipes and hoses in the hot–cold water circulatory system were selected to withstand 150 °C.

The control of the hot water and the cold water systems are separate. On the basis of cold water system has been consisted of the classic air-cooled heat transfer system from water to air. An electric water heater of 2 kW has been used to heat to the water in the hot water tank. Two classic cooling systems have been used to achieve a more powerful cooling. The sensing of the hot–cold water temperatures has been carried out by T-type thermocouples and their controls have been executed by the E-72 temperature controllers of Elimko Company as on–off controlled. Their hysteresis range has been selected 3 °C. Two motor, which are three-speed stage, one phase and of 80 W, have been used for circulation of the hot–cold water.

Another factor that is effective into electric production from TEGs is flow. Flow measurements have been carried out by two

ARF-4 HH flow meter of Mikronet Company. Measuring range of the flow meter is 0.5–15 m³/s.

The sizes of the used water tanks are 49×69×60 cm in the hot–cold water circulator system. While the hot and the cold water inert and pass through the hot and cold surfaces of the TEG, affect each other and between them is the exchange of heat. Minimize of the interaction has been provided with isolation that 1 cm thick Styrofoam placed their between and surroundings. Experiments have been carried out in different operating states of the hot–cold water system and temperature variation is given in Fig. 4. When ambient temperature is 20 °C, the hot–cold tanks have been filled with water and the cooling system is run, the cold water temperature could be reduced up to about 5 °C at the 6 h. In this case, after a small swing decreasing about 2 °C, the hot water tank temperature has remained at about 15 °C. In the same way, when ambient temperature is 20 °C, the hot–cold tanks have been filled with water and the heating system is run, the hot water temperature could be raised up to about 93 °C at the 6 h. In this case, after a small swing increasing about 2 °C, the cold water tank temperature has remained at about 19 °C. As shown in Fig. 4, when the hot–cold systems are run together, their temperatures have been reached at 7 h. In this case, the hot water temperature was about 93 °C and the cold water temperature was about 5 °C. The conclusion of them, the hot–cold temperatures in tanks did not almost affect each other through the insulation.

3. TEG data acquisition and SCADA

3.1. Set up of TEG data acquisition and test system (TEG-DA-TS)

A TEG data acquisition and test system (TEG-DA-TS) has been established to monitor and register to the data obtained from the TEG, as shown in Fig. 5. The TEG-DA-TS components mounted DIN rail have been consisted of a power supply of 24 VDC, a PLC, a expansion module (EM) of thermocouple, a voltage transmitter, a current transmitter, a OP, a PLC-OP communication cable, PLC-PC communication cable, a PC and two follow meters.

The system power has been provided with the seamless power supply of 24 VDC. The hot–cold surface temperatures, the ambient temperature T_A and the entering water temperature T_{LC} have been measured four T-type thermocouples. Four thermocouples have been connected the S7-200 CPU224XP PLC via the EM231. Analog temperature signals have been converted and processed into

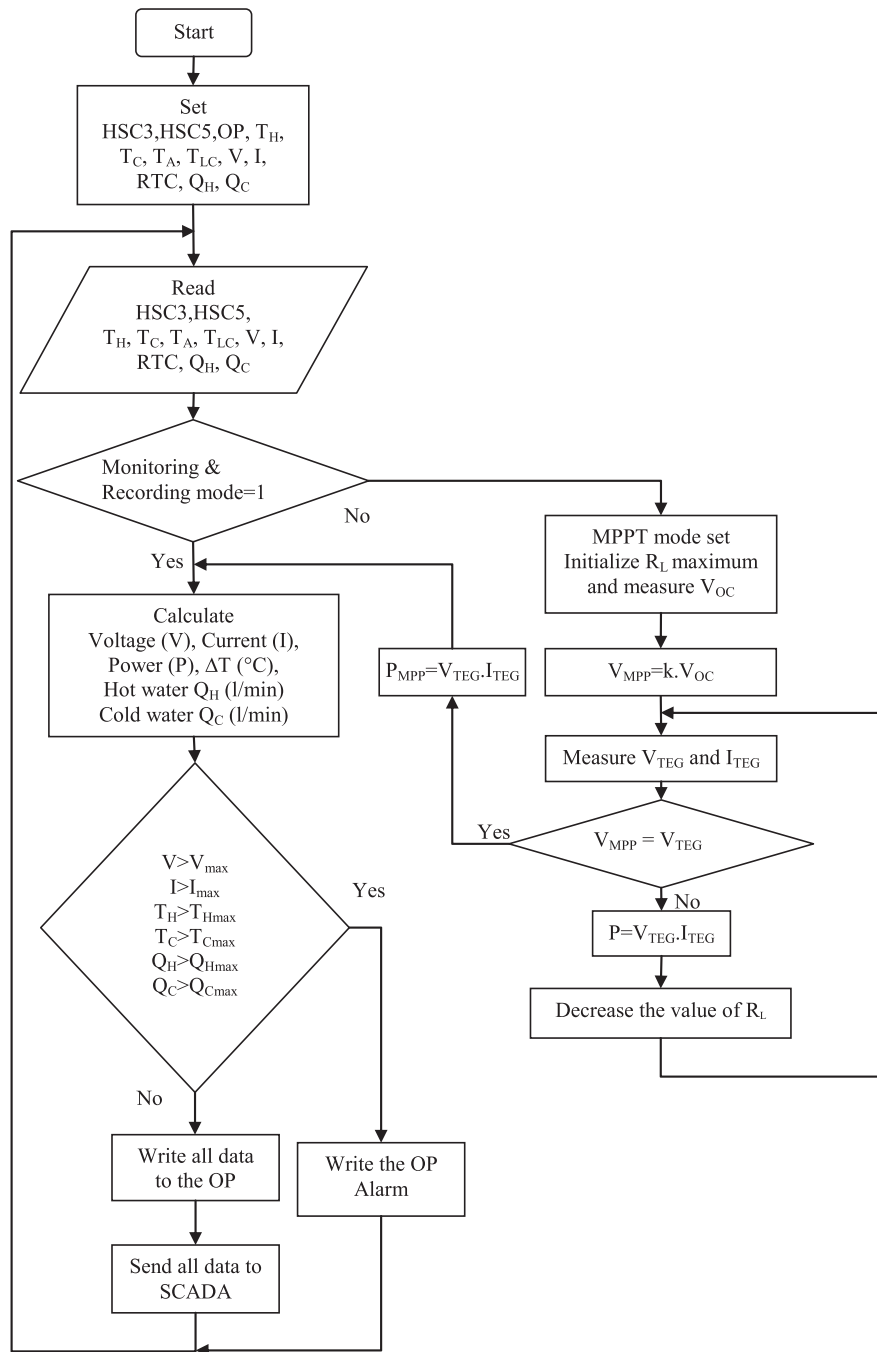


Fig. 6. Flow diagram of PLC program.

digital signals by the EM231. A WAS2 CMA 5/10 A DC current transmitter branding WeidMüller and a MCR-VDC-UI-B-DC voltage transmitter branding Phoenix Contact have been used for sensing amount of current and voltage obtained from the TEG, respectively. Owing to the used current–voltage transmitters, up to 10 A DC and 550 V DC voltage values can be sensed, respectively. AN0 and AN2 analog inputs of PLC have been carried out to convert the current and voltage values into digital values. The system will be utilized on the high power TEG of 1.5 kW. Two flow meters have been used to measure the flows of water passed from the cold-hot surfaces of TEG and their pulses have been connected to the DI1 and DI4 inputs of PLC directly. For sensing the pulses of flow meters, two high speed counters of PLC have been used.

Monitoring of all data of TEG has been carried out by a TD200 OP branding Siemens and a SCADA program. The used OP has

two-line and each line has 20 characters. Also, there are function keys on it. The four temperatures, the temperature difference between surfaces, current, voltage, power, the hot–cold flows and efficiency calculations have been monitored through the OP in real time. The calibration of current, voltage and temperatures were carried out by the Fluke 725 Multifunction Process Calibrator device. The flow of hot and cold fluid was measured with an accuracy of approximately 1% by the ARF-4 turbine flow meters.

3.2. The PLC program

The used Siemens S7-200 PLC in the TEG-DA-TS is the main component. The PLC program has been written by the MicroWin program. Data inputs of PLC are the hot–cold flows, the hot–cold surface temperatures, ambient temperature, the entering water temperature, output current and output voltage of TEG.



Fig. 7. SCADA program page.

There are two communication ports on the used PLC. Owing to these communication ports, the PLC data have been both monitored from the OP and transferred to the PC SCADA program. If a single-port PLC had been selected, the OP and SCADA could not have been used at the same time.

The PLC program algorithm is given in Fig. 6. TEG's current and voltage outputs have been connected to the AI0 and AI2 inputs of the PLC, respectively. The current-voltage transmitters have been calibrated for the 0–10 V analog output. Owing to the PLC has a 16-bit registers, the analog current-voltage data has been converted into 16-bit numbers. After the necessary scaling current, voltage and power values have been calculated and transferred to the OP and SCADA. DI1 and DI2, which are high speed counter (HSC) inputs of the PLC, have been used for the hot-cold flow pulses. DI1 is the HSC3 input and DI4 is the HSC5 input. Without these HSCs being initiated, the HSCs have been configured to count the flow pulses continuously. Interruption pulses or cut-offs in the HSC3 and HSC5 have been setup for every 10 pulses. The Counter 0 (C0) and the Counter1 (C1) have been increased by one value for the hot water flow rate and the cold water flow rate with every interruption, respectively. Also in order for an interruption pulse to be formed at the end of every 10 pulses, HSC3 and HSC5 have been setup. The PLC has been set up at real time clock (RTC) so as to enable the calculations of the L/min flow rates to be obtained. AI4, AI6, AI8 and AI10 inputs of the PLC have been configured to sense four temperatures. The temperature records have been sensed up to 350 °C by T-type thermocouples.

The OP program has been written by the wizard of the Micro-Win program. There are four menus on the OP: the calculations, flows, L_V_P and temperatures. The point to point interface cable (PPI-485) has been used to transfer all data from the PLC to the PC SCADA program.

Variations in load and temperature can cause a TEG to operate at a voltage that does not produce the maximum possible power for a given temperature difference. Therefore a maximum power point tracker (MPPT) is used to force the generator to a voltage that produces maximum power. There are many MPPT algorithms that are suitable for use with a TEG, most of which have been adapted from those used by a PV [19]. One of these is a fractional open-circuit voltage method that we used this method. The fractional open-circuit voltage, more commonly known as constant voltage, uses

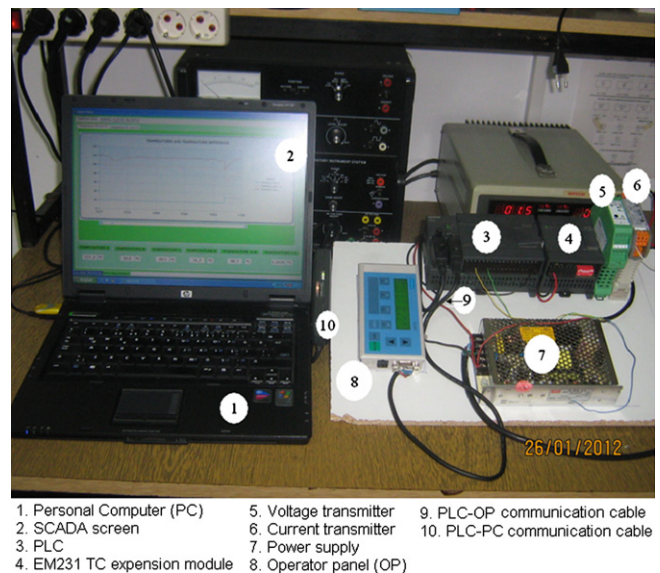


Fig. 8. Established TEG-DA-TS system.

the fact that the relationship between the open-circuit voltage (V_{OC}) and the TEG maximum power point voltage (V_{MPP}) is nearly linear, as shown by the following equation:

$$V_{MPP} = kV_{OC} \quad (1)$$

where k is constant. Usually $k = 0.5$ since the I - V characteristics of a TEG are almost linear, as shown in Fig. 10. The value of k was taken as 0.5 in the MPPT algorithm. The algorithm was operated by a maximum resistance of electrical load R_L and measuring V_{OC} . Eq. (1) was then used to calculate V_{MPP} . Until the V_{TEG} is matched to V_{MPP} , instantaneous power is calculated, then R_L is decreased, and it continues the MPPT loop. When the V_{TEG} is matched to V_{MPP} , maximum power point power P_{MPP} is calculated and finishes to the MPPT loop.

3.3. The SCADA program

The SCADA program interface page is given in Fig. 7. The SCADA program has been written by the WinTr SCADA program software. The SCADA program consists of four pages: Temperatures, flows, $V_{I_P_R}$ and all data. The user can easily get access to the TEG data via the SCADA pages and buttons.

The TEG parameters processed in the PLC have been transferred to the commercially available SCADA program via the RS485 communication line. Owing to the SCADA program, all the data of TEG have been visualized on the PC. The transfer process has been done from serial port of the PC via using the RS485 communication protocol at 9600 baud/rate. Current, voltage, power, the cold-hot temperatures, the temperature differences, the hot-cold flow rates and the flow differences values have been registered for “a second” time periods by the MySQL database in the SCADA program. The data has been programmed as historical and their graphics have been drawn to make a retrospective analysis. Analyzer can easily be seen via the changes in the system with help of the graphs. The reporting of the data desired time intervals can be done in order to be used later on. The alerts and warnings have been added to the SCADA program in order to enable users to communicate failures that may be in the system.

4. Implementation and experimental results

The established TEG-DA-TS is given in Fig. 8. Power, current and voltage performance graphs of the test results obtained from the SCADA program are given in Fig. 9, only one of the modules used the Altec brand for various temperature differences. The data sources of the curves are the data savings in the MySQL database to be analyzed. In Fig. 9, the maximum current I_{SC} is when value of the load resistor R_L is equal to zero and the maximum voltage V_{max} is when value of the load resistor R_L is infinite.

The generated maximum power P_{max} and the taken maximum efficiency η_{max} in the Altec datasheets are equal to 7 W and 3.5% in the temperature difference of $\Delta T = 100^\circ\text{C}$, respectively. Experimentally, the highest power value has been received when the value of the load resistor is $R_L = 0.72\Omega$, and the value is about 6.71 W. In this case, the input power is $Q_H = 197$ W and efficiency of TEG have been found to be $\eta_{max} = 3.4\%$. When the temperature difference between surfaces of the TEG is $\Delta T = 50^\circ\text{C}$, the generated maximum power and the taken maximum current have decreased and hence the generated power have diminished.

Current, voltage, power curves, which have been obtained from data that was registered and transferred from the TEG-DA-TS to the SCADA program and depending on the difference temperature, are given in Fig. 10. The temperature difference of the TEG has been raised from $\Delta T = 10^\circ\text{C}$ to about $\Delta T = 85^\circ\text{C}$. During the experiment, the value of the load resistance has been kept constant in $R_L = 2\Omega$.

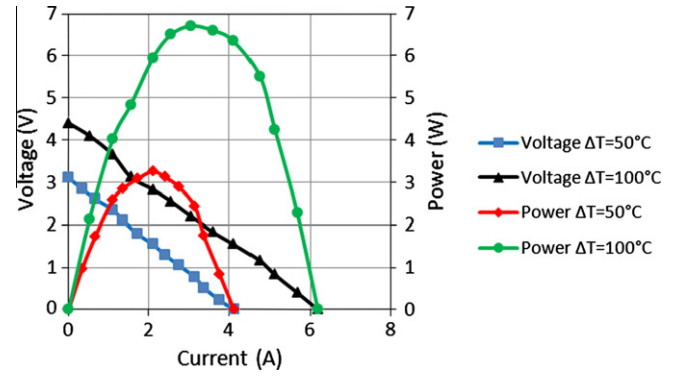


Fig. 9. Current, voltage, and power curves consisted of the data obtained from the SCADA in the various temperature differences ΔT ($^\circ\text{C}$).

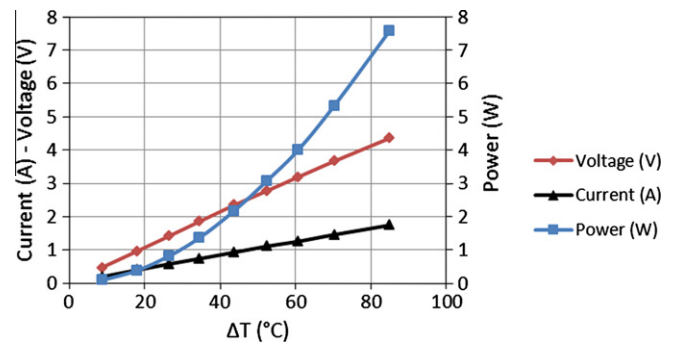


Fig. 10. Current, voltage, and power curves in the various temperature differences obtained from the SCADA.

While the current value is $I = 0.19$ A at $\Delta T = 10^\circ\text{C}$, it is $I = 1.75$ A at $\Delta T = 85^\circ\text{C}$ and it consequently has increased linearly. Also, while the voltage value is $V = 0.45$ V at $\Delta T = 10^\circ\text{C}$, it is $V = 4.35$ V at $\Delta T = 85^\circ\text{C}$ and it consequently has increased linearly. However, while the power value is $P = 0.09$ W at $\Delta T = 10^\circ\text{C}$, it is $P = 7.58$ W at $\Delta T = 85^\circ\text{C}$ and it consequently has increased nonlinearly.

5. Conclusion

A TEG-DA-TS has been designed for the calculation of the performance of the TEG depending on the data received from the TEG and it has been applied on the pre-installed TEG system of 10 W. A SCADA program that has been written for monitoring and recording of the measured TEG parameters such as the hot-cold side temperatures, the hot-cold water flow rates, current, voltage and power values via the PC. An OP program communicating with the PLC has been written and implemented in order to instantly monitor the data independent of the PC. A hot-cold water circulator system has been established to enable carrying out the TEG experiments in the laboratory. TEGs, Altec-GM-1 brand-coded have been examined with TEG-DA-TS and the values of maximum power P_{max} and efficiency were found. When the obtained results were compared with the TEG datasheets, the relative error for the maximum power was around 4% and the value for efficiency was below 3% by TEG-DA-TS.

In prospective study, the developed TEG-DA-TS will be used with more high-power TEG systems such as 100 W, 1.5 kW.

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